Earth’s Radiation Belts: A Tutorial

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Atmospheric Coupling

Thermosphere

$N_2 + e^*, p^*$

$N_2 + N', N$

$O_2$

$NO$

$NO_2$

$NO + O_2$

$NO_2 + O_2$

$O_3$

$NO_y$ Production

$NO_y$ Transport

Catalytic $O_3$ destruction by $NO_y$
Outline of Talk

I. Introduction

II. Key Observational Results
   - Coronal Mass Ejections
   - High-Speed Solar Wind Streams

III. Radiation Belt Particle Acceleration
   - Local Heating Processes
   - Radial Diffusion
   - Numerical Simulations

IV. Electron Losses and Atmospheric Coupling
   - Loss Processes
   - Atmospheric Chemistry Effects

V. Future Programs and Summary
Earth’s Radiation Belts

Some Frequently Used Platforms

**SAMPEX**
- LEO orbit ≈ 600 km

**POLAR**
- Elliptical 2x9 R_E Orbit

**GEO**
- Geostationary Earth Orbit – 6.6 R_E
Magnetospheric Regions and Currents
Key Observational Results
Solar Cycle View of Solar Wind Effects

Amazing control: \( V_{sw} > 500 \text{ km/s} \)!!
Coronal Mass Ejection - Earth Impact

Courtesy of NASA
Relativistic Electrons & Geomagnetic Storms

- **Recovery phase**
  - Increased fluxes
  - Energization
- **Main phase**
  - Flux dropout
  - Adiabatic field change & particle loss
- **Flux changes**
  - Decrease or no change in about 50% of storms
    - GEO data

[See Kanekal et al., 2004; Reeves et al., 2003]
Relativistic Electrons: Global Coherence

Kanekal et al. [2001]
SOHO Images of the Sun: Halloween 2003
Creation of New Radiation Belt

[Baker et al., 2004, 2007]
IMAGE EUV Plasmasphere Data

Data courtesy J. Goldstein

Baker et al. (Nature, 2004)
Coldest Plasmas Control Hottest Particles!

a. Normal plasmasphere/radiation belt location under typical conditions

b. Distorted plasmasphere/radiation belt during October/November 2003 storm


Exceptionally high solar wind speeds!

(Yohkoh soft X-ray images)
White arrows indicate 27-day recurrent events:
High-speed solar wind streams

1994 – High Speed Stream Control

Strong electron acceleration in the approach to sunspot minimum
Relativistic Electrons: Energization

- High solar wind speeds ( > 500 km/s) and southward $B_z$
- Substorm-generated seed population (extending to hundreds of keV)
- Physical processes
  - radial transport
  - in-situ acceleration

Baker et al., (ASR, 1998)
Anik Failures: Deep-Dielectric Charging

Many operational anomalies in 1994 period

- Late 1993 and early 1994 were remarkable times for $V_{SW}$
Some Key Questions About “Killer” Electrons

Are they really killers?
    …or just misunderstood?

Did they start out bad?
    …or did they have an unfortunate home life?

If they are killers?
    …was it self-defense?

Will the Boulder police and crack NOAA security forces combine…
    …to solve the mystery of the killer electrons?
Electron Acceleration
Adiabatic Invariants

Associated with each motion is a corresponding adiabatic invariant:

- **Gyro:** $M = \frac{p^2}{2m_0B}$
- **Bounce:** $K$
- **Drift:** $L$

If the fields guiding the particle change slowly compared to the characteristic motion, the corresponding invariant is conserved.
Inner Magnetospheric Particle Properties

The inner magnetospheric particle population may be completely characterized at a point in time by its distribution function:

\[ f = f(x, y, z, p_x, p_y, p_z) \]

Also referred to as the phase space density, \( f \) gives the number of particles in a volume \((x+dx, y+dy, z+dz)\), with momenta between \((p_x+dp_x, p_y+dp_y, p_z+dp_z)\).

The flux in a region of space may be related to the distribution function through

\[ f = \frac{j}{p^2} \]
Transport in M, K: Local Heating
Shear Waves and Particle Acceleration

- Limited local time: propagating waves dusk and counterpropagating waves dawn still lead to energization
Acceleration by Radial Transport

Nonrelativistically, and in a dipole,

\[ M = \frac{p^2}{2m_0B} = \frac{WL^3}{B_0} \]

or

\[ W = \frac{MB_0}{L^3} \]

so transport in \( L \) while conserving \( M \) will necessarily lead to change in energy, \( W \).
Transport in $L$: Radial Transport
Boundary Conditions: The Plasma Sheet as an Outer Boundary Source?

- keV electrons in the plasmasheet convect inward: $W$ increases $\rightarrow$ more grad-$B$ drift
- Alfven layer marks boundary between open and closed trajectories; $r_0$ increases with $M$, decreases with convection $E$
- $r_0$ for MeV geosynch electron *beyond magnetopause*
- Wish to investigate whether and when plasmasheet electrons may act as a source of MeV radiation belt particles

N. Tsyganenko

*Elkington et al. (JASTP, 2004)*
MHD Simulation of a Strong Storm

[Courtesy M. Wiltberger]
MHD/Particle Simulations of Energetic Electron Trapping

- 60 keV test electrons, constant $M$
- Started 20 $R_E$ downtail, 15s intervals
- Evolves naturally under MHD $E$ and $B$ fields
- Removed from simulation at magnetopause
- Color coded by energy
Electron Losses

Radiation Belt Mapping
2-6 MeV electrons in the magnetosphere
Rapid Radiation Belt Depletions

Baker et al. (2006)
SAMPEX: 2003-2005 E: 2- to 6- MeV

$e \text{[cm}^2 \text{sr sec]}^{-1}$

Doy 2003

[Baker et al, GRL, 2007]
Sources of Atmospheric Ionization

Atmospheric Particle Coupling

- Solar EUV and X-rays
- Auroral Electrons
- Relativistic Electrons
- Solar Proton Events
- Galactic Cosmic Rays

Ionization Rate (cm$^{-3}$ s$^{-1}$)

Altitude (km)
Future Programs and Summary
The Radiation Belt Storm Probes (RBSP) program

Science Objectives:
1. Differentiate among competing processes affecting the acceleration and loss of radiation belt electrons;
2. Understand the creation and decay of new radiation belts;
3. Quantify the relative contribution of adiabatic and nonadiabatic processes;
4. Understand the role of “seed” or source populations; and
5. Develop and validate specification models of the radiation belts.

Radiation Belt Storm Probes (RBSP) constellation

RBSP addresses the scientific and programmatic goals of the NASA Living With a Star program.
International Living With a Star Program (RBSP and ORBITALS)
Summary

• We have a long and intriguing record of Earth radiation belt observations
• Rapid, powerful particle acceleration can occur on short time scales within the radiation belts
• Both local heating and radial transport are important
• Powerful losses can lead to coupling with the deeper atmosphere
• New missions that are underway should lead to remarkably good science closure in the near future, more than 50 years after James Van Allen’s pioneering discoveries
Thank you—Questions?
Top Ten Reasons to Worry About Radiation Belt Changes

10. Communication satellite disruptions prevent C-Span from showing Congress at work. (No one notices).
9. Large solar wind stream event and electron enhancement causes New York cab drivers to speak perfect English.
8. High particle radiation on space shuttle makes Coca-Cola taste just like Pepsi.
7. Magnetic storm sends crazed homing pigeons on a pecking rampage.
6. Pipeline corrosion interrupts flow of Cheney/Bush retirement funds from Iraq.
5. Solar particles in outer belt cause Barack Obama to lose all judgment: Stars in really bad TV movie called “Solar Flare 2009”.
4. Hubble Space Telescope has upset in South Atlantic Anomaly and can only be pointed at Osama bin Laden’s cave.
3. Increased atmospheric-energetic electron coupling causes Air Force One to make emergency aircraft carrier landing.
2. Radiation belt enhancement causes Katie Couric to do CBS Evening News in thick Italian accent.

And the Number 1 reason to worry about rad belt changes:
1. Astronauts go berserk in zero-gravity pie eating contest!